

Ventilation and Infiltration in High-Rise Apartment Buildings

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Synopsis: Air flow, air leakage measurements and numerical simulations were made on a 13-story apartment building to characterize the ventilation rates for the individual apartments. Parametric simulations were performed for specific conditions, e.g., height, orientation, outside temperature and wind speed. Our analysis of the air flow simulations suggest that the ventilation to the individual units varies considerably. With the mechanical ventilation system disabled and no wind, units at the lower level of the building have adequate ventilation only on days with high temperature differences, while units on higher floors have no ventilation at all. Units facing the windward side will be over-ventilated when the building experiences wind directions between west and north. At the same time, leeward apartments did not experience any fresh air--because, in these cases, air flows enter the apartments from the corridor and exit through the exhaust shafts and the cracks in the facade. Even with the mechanical ventilation system operating, we found wide variation in the air flows to the individual apartments. In addition to the specific case presented here, these findings have more general implications for energy retrofits and health and comfort of occupants in high-rise apartment buildings.

1.0. Introduction & Literature Review

Quantifying the impact of infiltration on energy use in buildings has stymied researchers and practitioners alike. And while the difficulties of measuring and modeling its effect are widely acknowledged, there is agreement on its importance. The effect of infiltration on energy use in a high-rise apartment building can be seen directly in **Figure 1**. The figure plots annual energy consumption per floor in a 12-story apartment building in Pittsburgh, Pennsylvania. The energy consumption on the lower floors is 28% higher than the mean, and decreases with height until the next-to-the-highest floor where the consumption is 32% lower than the mean. (Energy consumption on the top floor is higher due to conduction losses through the roof.) The reason for this variation in energy use is the infiltration due to stack effect--because of pressure differentials due to inside-outside temperature differences, air in the building rises up the vertical shafts (stairs and elevators) and draws in colder outdoor air at the base of the building. So lower apartments get a greater burden of outdoor air which poses an energy penalty in

winter, while the upper units get warm air from below, but the lack of outdoor air to these units poses an indoor air quality penalty.

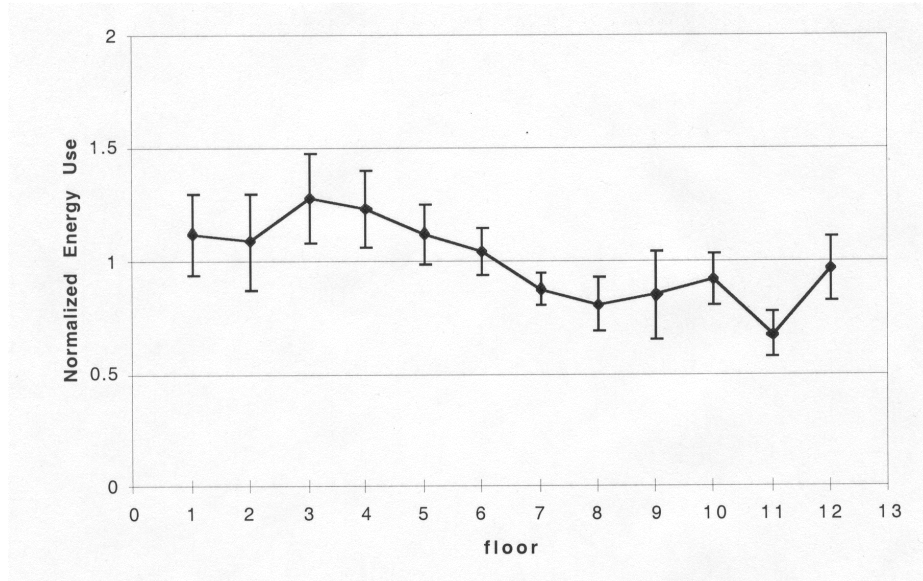


Figure 1. Annual electricity consumption per floor for a 12-story apartment building in Pittsburgh, Pennsylvania. Consumption data have been normalized by mean values. Error bars show one standard deviation above and below the mean.

To address these issues of balancing energy efficiency and health, multi-story residential buildings often have mechanical ventilation systems to provide adequate outside air for comfort and health. The performance of these systems, however, is often less than satisfactory, due to poor design, sporadic maintenance, and interactions with both natural infiltration and occupant behavior.

The literature on air flow and air leakage measurements in high-rise multifamily buildings is quite limited. As we are not aware of any review of these topics for North American multifamily buildings (both highrise and lowrise), we present a brief chronological summary of the research on these topics below.

A pioneering study by Tamura and Wilson measured the pressures across the exterior envelope of a nine-story building in Ottawa, Canada (Tamura and Wilson, 1966). They made measurements with the mechanical ventilation system both on and off, and concluded that the pressure differences across the building envelope depends on the

distribution of the openings in the envelope and the ratio of resistance to air flow inside the building to that across the exterior wall.

An early study on measurements of air leakage in multistory apartment buildings was performed by C.Y. Shaw in 1980. He conducted small-scale pressurization tests on the exterior walls of apartments in a multi-story building and found floor-wall joints, windows and window sills to be the major leakage sites (Shaw 1980).

One of the first measurements of both air leakage and infiltration in a high-rise apartment is reported by Feustel et al. (1985), where fan pressurization, tracer gas and pressure measurements were made in a 9-story dormitory building in Berkeley, California. The measurements were then used in an airflow simulation model to study the importance of both wind and stack effect in determining air infiltration.

Using tracer gas measurements in three typical low-income apartment buildings in New York City, Commoner and Rodberg found natural infiltration rates of 1.08, 0.58 and 1.01 ACH, about twice the leakage calculated from window dimensional measurements. They determined that the "extra" leakage was to adjacent apartments and common spaces (Commoner and Rodberg, 1986).

Modera et al., working with staff from the Minneapolis Energy Office, measured air leakage in a six-unit building in Minneapolis (Modera et al., 1986). Using six blower doors simultaneously they showed that the average leakage for each apartment was 1600 cm^2 ($13 \text{ cm}^2/\text{m}^2$) and that only 40% of the air leakage was directly through the exterior envelope. The remainder was either to the adjacent units or in the interstitial spaces between the apartments. These leakage areas were used in conjunction with a multizone air infiltration model to determine the air flows between apartments and to the outside.

Two blower doors were used to measure air leakage in two three-story apartment buildings in Chicago (Diamond et al., 1986). Leakage areas of 2460 cm^2 and 1880 cm^2 were measured for the two apartments, which when normalized by floor area were both

19 cm²/m². While the apartments were significantly leakier than the one measured by Modera, roughly the same fraction (60%) of the leakage was to the other apartments.

Blower door measurements in a study of eleven multifamily buildings in upstate New York showed an average pre-retrofit leakage rate of 35.5 ACH @ 50 Pa, implying a natural ventilation rate of over 1 ACH (Synertech, 1987).

Bohac and his colleagues tackled a six-story apartment building in Minneapolis, Minnesota in 1987 with several tracer gas and fan pressurization techniques. They were able to estimate airflows between apartments, but concluded that in this building, air exchange was dominated by patterns of window openings (Bohac, 1987).

Researchers in the Pacific Northwest took measurements in nine new motel-style multifamily buildings (where each unit has its own outside door) and reported estimated average leakage rates ranging from 0.08 to 0.30 (median 0.19) ACH, well below the ASHRAE 62 Standard of 0.35 ACH (Baylon and Heller, 1988).

Measurements of low-income rowhouses in Philadelphia showed an extremely high air leakage of 55 ACH @ 50 Pa, with up to 30% of the flow to adjoining units (Cameron, 1990). They attributed the high leakage to the characteristics of the row house construction and the generally poor condition of the houses.

Researchers found that even in a two-story apartment building that ground-floor apartments can have more than double the heating bills of upstairs apartments due to internal air-leakage patterns and heat flow (McBride et al., 1990).

Modera and Herrlin analyzed inter-zonal leakage using two blower doors in a controlled test set-up. These data were used in a computer simulation (Movecomp) to determine air flows in a multifamily building under different wind conditions and measurement protocols. They found that uncertainties due to wind fluctuations for wind speeds under 5 m/s did not exceed 10% (Modera and Herrlin, 1990).

Shaw and his colleagues in Canada measured two high-rise apartment buildings using a system of two pressurization set-ups and tracer gas equipment. One blower door was used in the individual apartment and the other was used to pressurize the entire building. The pressures between the test unit and the adjacent units were balanced to minimize the air leakage between the party walls (Shaw et al., 1990).

Harrje et al. compared three different tracer gas techniques to measure air infiltration in a high-rise apartment in Princeton, New Jersey. The tests were Constant Concentration Tracer Gas (CCTG), Multi-tracer Mass Spectroscopy (MTMS) and Air Infiltration Monitors (AIMS). The study reports the strengths and weaknesses of the three methods (Harrje et al., 1990).

Hayes reports the results of an audit of a rehab of a four story brick warehouse converted to apartments for the elderly. The new construction consisted of sheet-rocked boxes inside the brick walls of the original building, with large spaces for air flow between the old and new walls. But the individual apartments tested quite tight for air leakage. Hallways tested tight, too. Her conclusions were to focus air sealing on bypasses--especially between old and new building envelopes, and concentrate on improving mechanical ventilation systems with dampers and better controllers (Hayes, 1992).

Mark Kelley (Kelly et al. 1992) measured the air leakage pre-and post-retrofit in a high-rise apartment in Revere, Massachusetts. They found an average pre-retrofit leakage for 17 of the apartments of 532 CFM at 50 pascals, and a post-retrofit leakage of 449 CFM at 50 Pascals, a reduction of 15%.

Perhaps the largest study to date on ventilation in multifamily buildings was conducted by the New York State Energy Research and Development Authority (Shapiro-Baruch, 1993). They developed and tested a ventilation audit in 10 multifamily buildings, finding measured airflow rates to be on average 32% less than the design values. Energy use for mechanical ventilation varied widely from building to building, from less than 2% to

more than 20%. They identified poorly designed and poorly operated supply air systems as the source of many indoor air quality problems.

Monitoring of two multifamily apartment buildings in Chicago, Illinois, was undertaken in the Spring of 1993 by a team of energy researchers from Argonne National Laboratory, the University of Illinois, and Lawrence Berkeley Laboratory. They performed ventilation and infiltration measurements in two multifamily apartment buildings to determine the leakage characteristics for two types of retrofits and adequate levels of ventilation for air quality throughout the building. In one of the two buildings, blower-door measurements showed relatively high air-exchange rates. Pressure measurements in wall cavities indicated that internal and exterior walls experienced pressures close to those outside. Construction details of the walls showed that the use of metal studs, with break-outs for electrical wires, provided holes that connected all wall cavities of a dwelling. Depressurization of one zone caused air flows from the outside through all direct flow paths and through all wall cavities to openings in the walls (e.g., electrical outlets), including interior walls. The building constructed with wooden studs had lower leakage levels. The pressure level for interstitial spaces was much closer to the level of the depressurized zone than to the ambient pressure (Katrakis et al., 1994).

Researchers from LBL used a single-blower-door technique for measuring leakage in multifamily buildings in 1993 in two New York apartment buildings. One apartment was pressurized and depressurized to ± 50 Pa, and the resulting pressures were measured in adjacent apartments. By incorporating the pressures measured in the adjacent apartments (1-15 Pa) into a mass balance equation, they were able to calculate that approximately 50% of each apartment's leakage was to outside in one building, and that a significantly larger fraction was to outside in the other (Dickerhoff et al., 1994).

Vicky Hayes and Ian Shapiro-Baruch report on a recently funded project by the New York State Energy Research and Development Authority (NYSERDA) to assess the types, effectiveness and energy efficiency of ventilation systems in multifamily buildings in New York State. They collected detailed information for ten sites and additional information on another 50 sites. They concluded that much of the uncertainty

surrounding ventilation codes and standards could be eliminated if an accurate method of quantifying air flow in a multifamily building was available (Hayes and Shapiro-Baruch, 1994).

What emerges from a review of these studies is the paucity of information characterizing air leakage in multifamily buildings and the typically poor level of control in the provision of ventilation for the building occupants. Several of the articles mention reasons for why there are problems in measuring, modeling and designing ventilation systems for high-rise multifamily buildings, but few offer any solutions. Routine questions from the single-family literature such as how to define a reference pressure for blower door measurements are currently unanswerable for multifamily buildings. And we have little knowledge on how to characterize and determine the leakage distribution in different types of multifamily construction.

2.0 Project Description

Our recent activity in this area came about through the DOE-HUD Initiative, a response to the U.S. National Energy Strategy's directive to improve the energy efficiency in Public Housing. Under the Initiative's guidance a collaborative project was established to demonstrate energy efficiency in Public Housing as part of a utility's Demand Side Management (DSM) Program.

The demonstration site is the Margolis Apartments, a modern 150-unit high-rise apartment building for the elderly and handicapped, located in Chelsea, Massachusetts, in the greater Boston, Massachusetts, metropolitan area (Figure 2).



Figure 2. The Margolis Apartments, Chelsea, Massachusetts.

The Margolis Apartment building was designed and built in 1973-1974 and is typical of high-rise construction from that period. The building has thirteen stories and is of steel-frame construction. The individual apartments have electric-resistance heaters in each room, and double-pane windows and sliding balcony doors. Figure 3 shows a typical floor plan of the building.

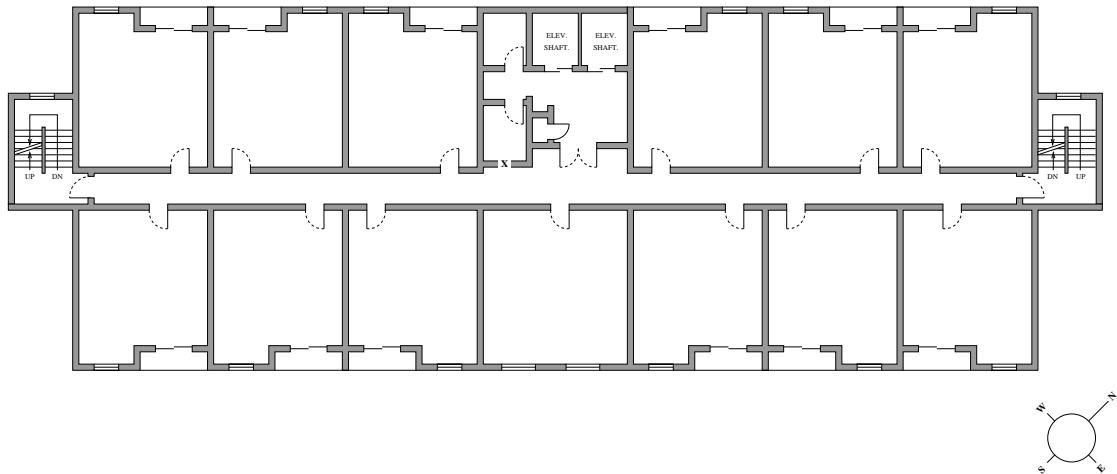


Figure 3. Typical floor plan (floors 6-12), Margolis Apartments, Chelsea, MA. The “x” shows the location of the supply ventilation register for each corridor.

The building has a mechanical ventilation system, with kitchen and bathroom exhaust fans for each apartment leading into separate vertical shafts which have additional exhaust fans located on the roof. The supply air system for the building is provided by a fan and heating unit on the roof that connects to a vertical shaft which has supply registers to the main hallway on each of the floors (Figure 4). Supply air then enters the apartments by a slot under the front door of each unit.

[Figure not included]

Figure 4. The central ventilation supply trunk and typical exhaust risers from kitchen and bathrooms, Margolis Apartments, Chelsea, Massachusetts.

The building is exposed on all sides to the wind, and is located less than 5 km from the airport weather station. Airport weather data records a mean annual wind speed of 6 m/s with up to 26 m/s wind speeds in winter. The winter wind is primarily from the northwest; the wind in spring through fall is from the southwest.

In December, 1992, the building underwent extensive retrofits. New double-pane, low-e windows replaced the old windows throughout the building. A computerized energy management system was installed that allowed for tracking and controlling of the thermostats in the individual apartments. Efficient light bulbs were installed in the individual apartments and in the parking areas. A new sprinkler system was installed throughout the building. The balconies were screened in to prevent the pigeons from roosting. A second phase of retrofit activity a year later involved improvements to the abandoned ventilation system.

Prior to the window retrofit, drafts were a major complaints expressed by the tenants, but since the retrofit, there have been--according to building management--fewer complaints about window drafts. There was mention of the windows being hard to open for some of the residents, both from the latching mechanism and the effort needed to lift the double-hung sash. No problems with condensation on the windows were reported since the retrofit.

The northwest-facing units (weather side) continue to be the hardest units to maintain thermal comfort. Also the second floor units (above the open parking areas) continue to be a problem in cold weather.

3.0 Measurements & Analysis

The measurements and analysis that we are reporting here consist of four parts: 1) Air leakage measurements of the apartments measured pre- and post-retrofit, 2) Air flow measurements of the apartments pre-retrofit, 3) Pressures and flows between the apartments and the circulation areas and 4) Computer simulations of the air flows in the building under different weather conditions.

3.1 Air Leakage Measurements

We measured the air leakage in nine apartments, before and after the new windows were installed. Figure 5 shows a plot of one of the air leakage measurements. The average pre-retrofit total effective leakage area for the one-bedroom apartments was 241 cm^2 and 256 cm^2 for the two-bedroom apartments. The post-retrofit total effective leakage area for the one-bedroom apartments was 230 cm^2 and 248 cm^2 for the two-bedroom apartments (Table 1).

Table 1: Leakage Areas Pre- and Post-Retrofit

Apartment	Leakage Area @ 4 Pascals(a) [cm ²]	
	<u>pre-retrofit</u>	<u>post-retrofit</u>
301 (2-bdrm)	228	240
313 (2-bdrm)	284	257
704	173	167
1102	280	-
1107	309	293
1211(b)	180	246
1213	238	215
1313(c)	205	278

(a) fit to $n=0.667$

(b) air conditioner in window post-retrofit only

(c) bedroom window not fully closed during post-retrofit test

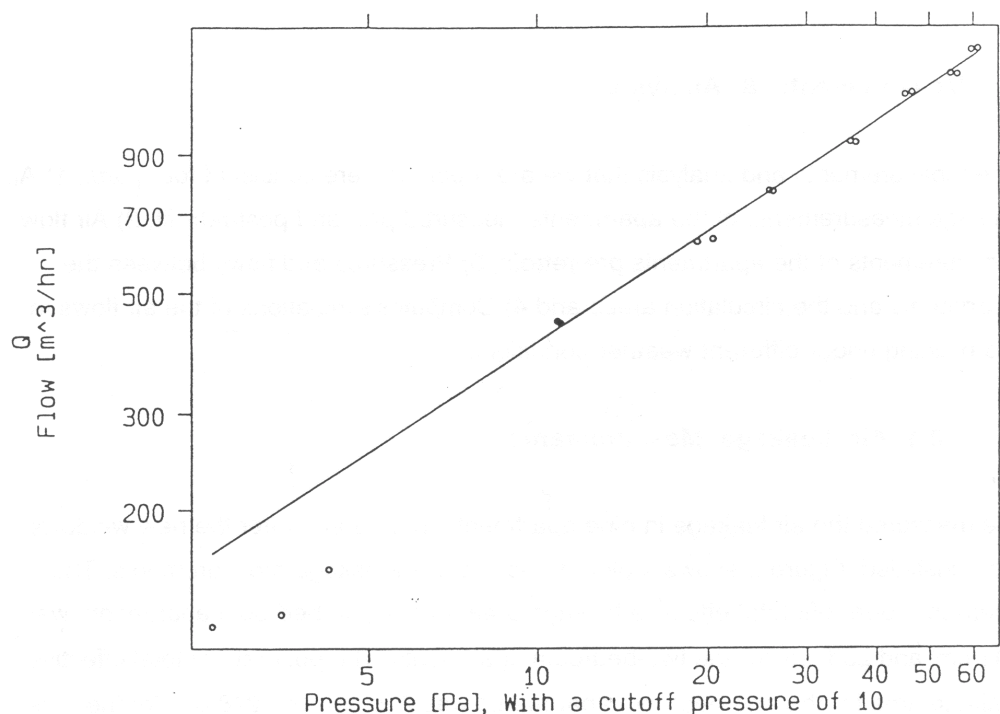


Figure 5. Air flow versus pressure from blower door measurements at an apartment on the 12th floor of the Margolis Apartments. The Effective Leakage Area (ELA) was 237 cm² at 4 pascals and 324 cm² at 25 pascals.

We found little or no reduction in air leakage due to the new windows, which is surprising given that tenants who had previously complained of drafts were now satisfied. One explanation is that tenants were previously experiencing down drafts at the window due to cold surface temperatures, which no longer occur because of the new double-pane, low-e windows.

We also note that these measurements, both pre- and post-retrofit, were made in very windy conditions--beyond the limits allowed for standard blower-door tests. While this problem is not uncommon in low-rise buildings, it is an even bigger problem in high-rise buildings, where wind speeds are often much higher than for buildings at ground level. Furthermore, the measurement technique being used is based on a reference pressure describing the pressure field around the building. In large buildings, it is very difficult to find a pressure point which acts as the reference pressure for the apartment being investigated. There is also the possibility that the measurement technique itself, i.e.,

depressurization with a blower door, temporarily seals the windows and distorts the findings.

By way of comparison, Kelley et al. (Kelly 1992) measured the air leakage pre-and post-retrofit in a high-rise apartment in Revere, Massachusetts, a few kilometers north of the Margolis apartment. They found an average pre-retrofit leakage for 17 of the apartments of 904 m³/h at 50 pascals, and a post-retrofit leakage of 763 m³/h at 50 Pascals, a reduction of 15%. The comparable flows at Margolis were higher, and showed no reduction after the retrofit, with an average of 1183 m³/h pre-retrofit and 1214 m³/h post-retrofit (Table 2).

Table 2: Air Flow Pre- and Post-Retrofit

Apartment	Air Flow @ 50 Pascals(a) [m3/hr]	
	<u>pre-retrofit</u>	<u>post-retrofit</u>
301 (2-bdrm)	1140	1204 (+5%)
313 (2-bdrm)	1416	1288 (-10%)
704	864	838 (-3%)
1102	1397	-
1107	1541	1469 (-5%)
1211(b)	901	1233 (+37%)
1213	1188	1076 (-9%)
1313(c)	1025	1394 (-)

(a) fit to $n=0.667$

(b) air conditioner in window post-retrofit only

(c) bedroom window not fully closed during post-retrofit test

3.2 Air Flow Measurements

Ventilation rates were measured using tracer gas in two apartments, pre-retrofit, in various configurations of exhaust ventilation. With no supply or exhaust ventilation we found typical rates to be about 0.2 ACH (Figure 6).

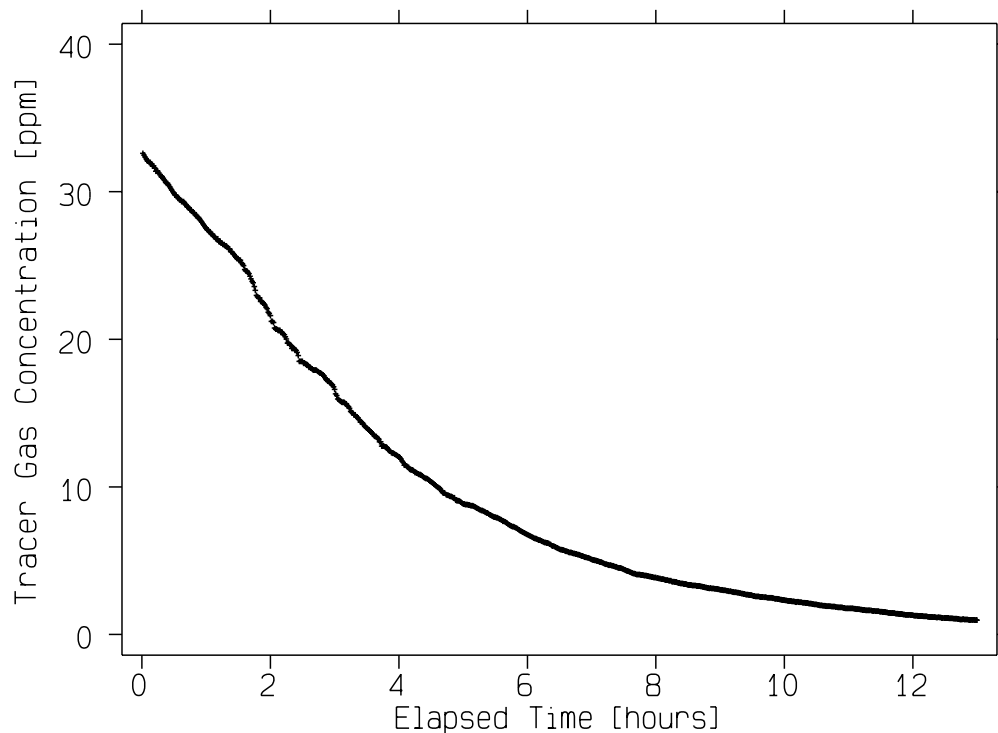


Figure 6. Tracer gas decay **without** supply and exhaust fans in operation for a unit on the 12th floor of the Margolis Apartments (June 12, 1992). The decay corresponds to an air exchange rate of 0.2 ACH.

We also measured the leakage from one apartment to another, using tracer gases, and found little communication between units--less than 4% of the total leakage was to adjacent apartments. This was not altogether surprising given the concrete construction of the building.

These ventilation rates are below the recommended 0.35 ACH given in ASHRAE Standard 62 . Operation of the building supply system and the exhaust systems increased the ventilation rate to 0.44 ACH (Figure 7). If the mechanical ventilation systems were operating at their designed flows, the apartment ventilation rates might well meet the ASHRAE standard without excess ventilation.

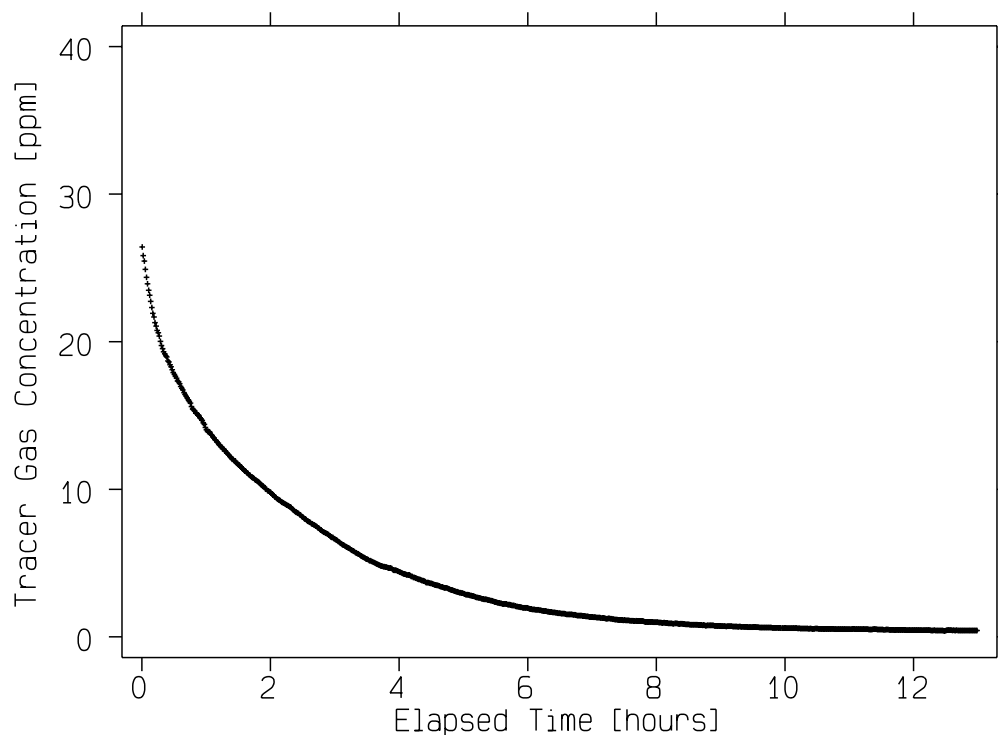


Figure 7. Tracer gas decay **with** supply and exhaust fans in operation for a unit on the 12th floor of the Margolis Apartments (June 13, 1992). The decay corresponds to an air exchange rate of 0.4 ACH.

We measured the exhaust air flow from the kitchen hoods and the bathroom vents using a hot-wire anemometer. The filter area of the kitchen hood was divided into 5 sub-areas and an average velocity for each area was determined. From the air velocity, the flows were then calculated. The air velocity was also measured for several locations in the three-slot arrangement of the bathroom exhaust.

The exhaust flows of the seven apartments investigated showed the following characteristics: 1) air flow at the kitchen exhaust register with both the roof exhaust fan and the building supply on, but with the local exhaust fan off, ranged from 50 to 170 cfm, with a mean value of 92 cfm, significantly higher than the design value, (see Figure 8), 2) air flow at the bathroom exhaust register was smaller than the kitchen exhaust flows, and ranged from 40 to 86 cfm, with a mean value of 53 cfm, 3) With the addition of the local exhaust fan operating, kitchen exhaust flows reach values between 170 to 200 cfm (mean = 188 cfm) and, 4) the air flow at the bathroom register with the local bathroom fan operating (together with the roof top exhaust fan) produced 110 to 140 cfm (mean = 122 cfm).

Under normal operating conditions, i.e., the local bathroom and kitchen exhaust off, the total exhaust flow in the apartments would be between 100 and 260 cfm (mean = 145 cfm). The mean air flow supplied to the apartments from the corridor was measured at 22 cfm, so on average, under these weather conditions, the apartment would be drawing in an additional 120 cfm of outside air through the exterior wall and windows. This over-ventilation suggests the need for lowering the roof exhaust fan flow rates.

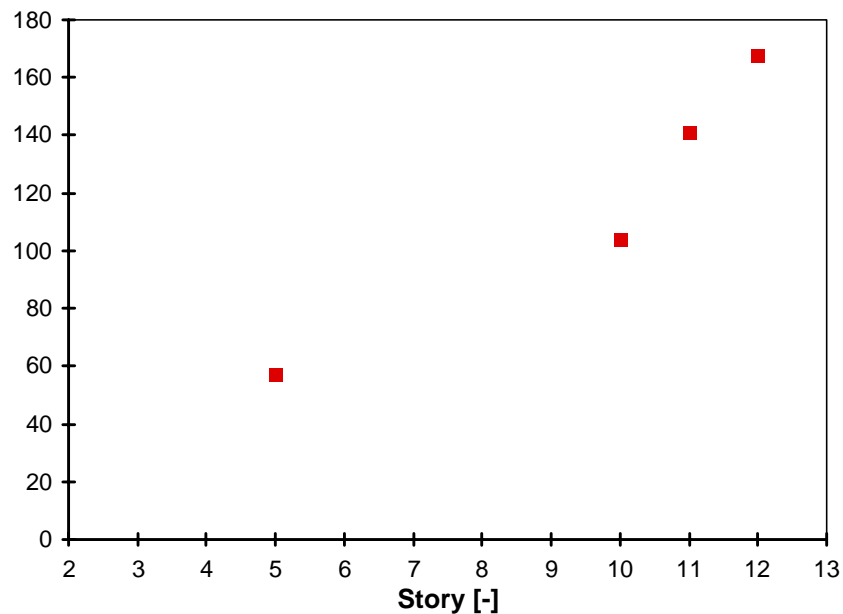


Figure 8. Kitchen exhaust air flow with the local exhaust fans off. Measurements were made at the same exhaust shaft at floors 5, 10, 11 and 12.

3.3 Temperatures, Pressures and Flows

We measured the temperature of the supply air at the hallway registers for floors 2-13, and they were all in the range of 28-30 °C (83-86) °F (see Figure 9). These temperatures were higher than the setpoint in the EMCS for the air supply, which is surprising, but in fact it serves as a more efficient strategy by providing air heated with the gas system than the individual electric units in the apartments and, it avoids cold drafts along the floor!

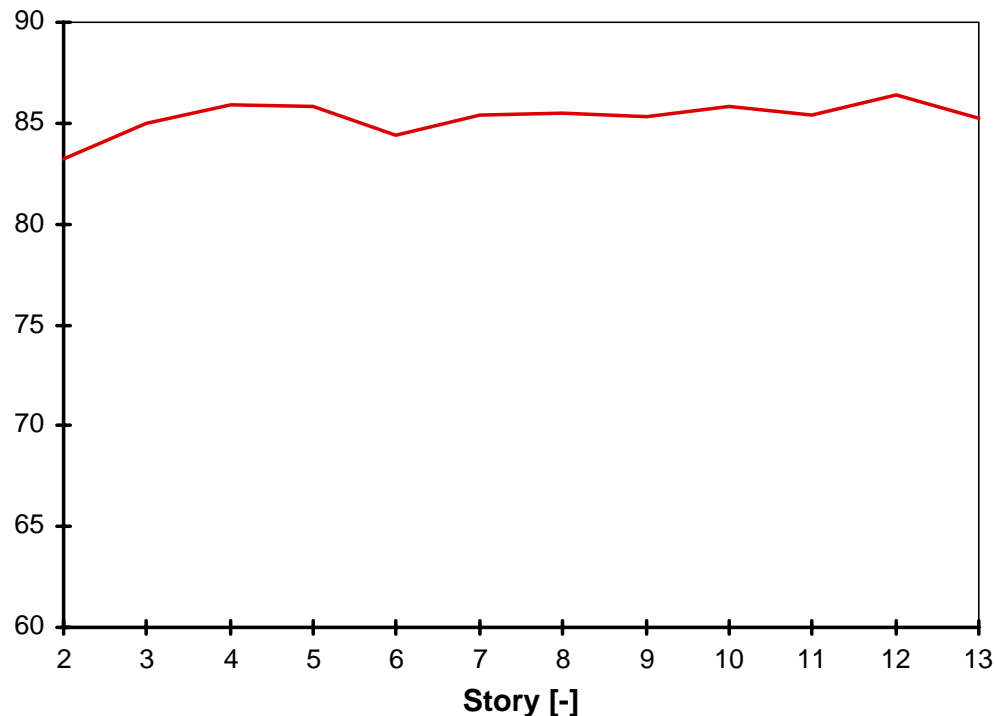


Figure 9. Supply air temperature measured at the hallway registers.

We also measured the supply air flows at the hallway registers and they were all within a range of 900-1300 m³/hr (530-760 cfm) per floor, with the average matching the design specification for the supply air flow (Figure 10).

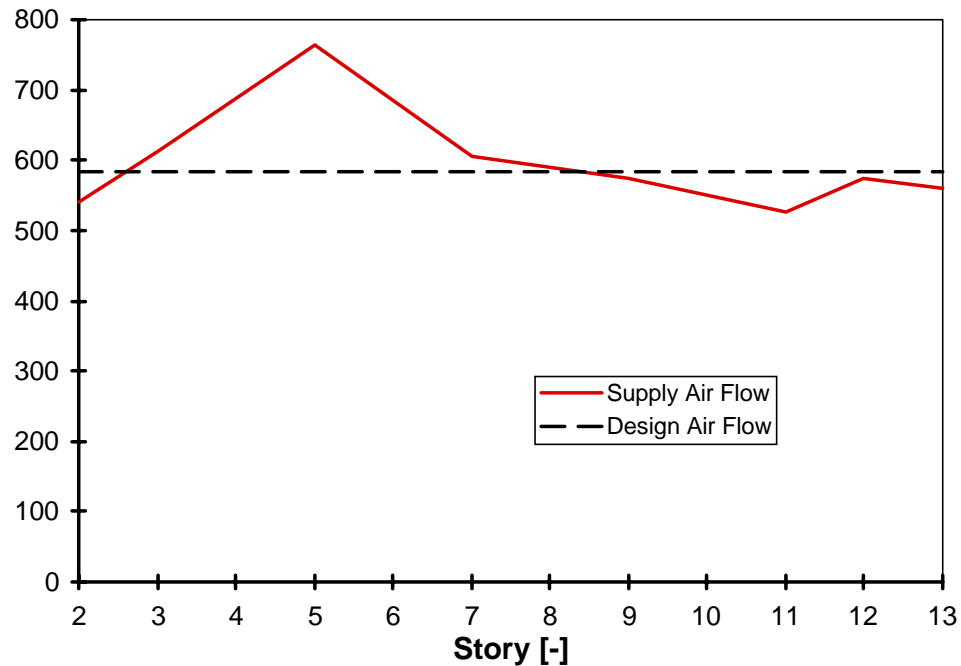


Figure 10. Supply air flow measured at the hallway registers.

The air velocity in the elevator shaft was measured at the top of the shaft at the floor of the penthouse elevator room (which has a large opening to the leeward side). The air velocities ranged between 0.7 and 1.5 m/s with both cabs running (regardless of direction) suggesting the air flow is determined more by wind and stack effect than by the movement of the cabs. The air flow at the top of the elevator shaft during the first measurement was out of the shaft, reversing direction later in the day, i.e., down the shaft, when the wind shifted direction from the northwest to the northeast.

Inside the building, the air velocity from the elevator shaft into the corridor ranged from 2 m/s at the 13th floor down to 0.7 m/s at the 3rd floor. The temperature in the elevator was 19 °C (66 °F) when the outside temperature was 7 °C (45 °F). The air velocity at the trash chute at the 13th floor, with the door open, was 4 m/s, upwards, another indicator of the stack effect in the building.

The pressures from the stairwells to the hallway follow the expected pattern of positive pressures to the outside above the neutral pressure level (roughly the midpoint of the building) and negative pressures below, with the profiles of both the north and south towers being similar. The pressure range from -4 to +8 pascals is relatively small, due to the relatively mild temperatures outside during the measurement 7 °C (45 °F) and the low wind speeds (Figure 11).

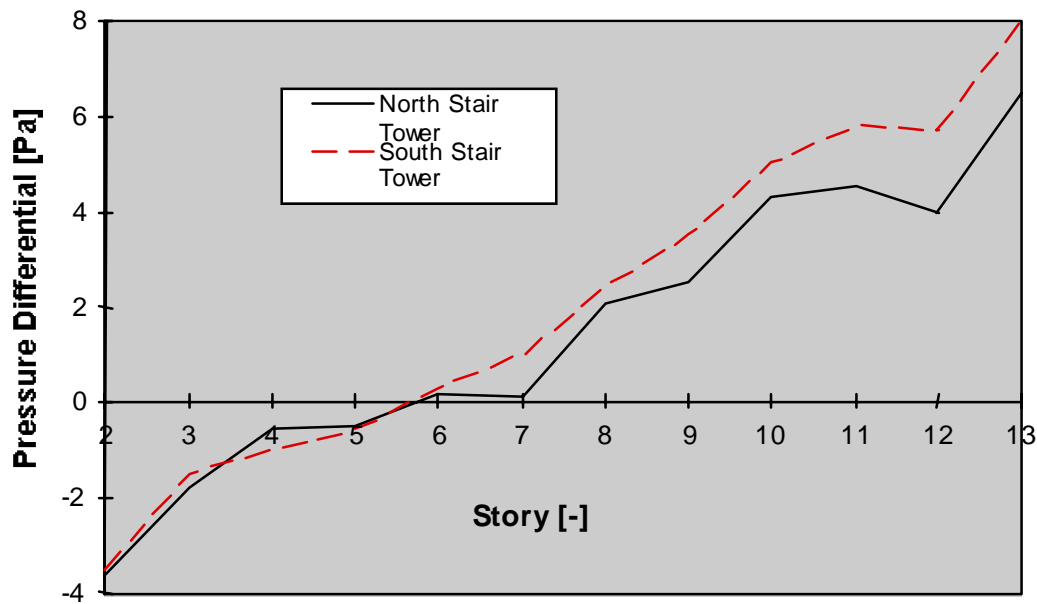


Figure 11. Pressure differences between the stair towers and the hallways.

3.4 Ventilation Simulations

Based on the measured air leakage data from the building we conducted extensive air flow modeling of the apartments using the multizone air flow model COMIS, a simulation tool, developed at Lawrence Berkeley Laboratory, which calculates air flows based on mass balance calculations for individual zones (Feustel, 1990). To make the simplified model, each floor was divided into four corner zones (one apartment each), one zone describing five apartments on the southeast facade, one zone describing four apartments on the northwest facade, one zone describing the hallway and one zone

each for the staircases and the elevator shaft. The supply shaft and the exhaust shafts were modelled as additional zones. Over one hundred zones were defined in the model (see COMIS input file "CHELSEA.CIF" in the Appendix) with 138 outside pressure points (wind pressure distribution) and 565 flow paths were necessary to describe the air flow patterns within the building. (CPU-time for nine different wind velocity / temperature difference combinations is 66 seconds on a SUN SparC ELC computer.) In order to limit the amount of input needed for the simulation model, each apartment was modeled as one zone, assuming the internal doors to be open. To account for the stack effect and the inter-zonal flows between the floors, all 13 floors were modeled.

The results show, that with wind blowing perpendicular to the windward side and no stack effect present, air moves from the windward side facade through the corridors into the leeward side apartments. Under the previous conditions with no ventilation system present, only a small portion of the infiltration air is exhausted through the vertical shafts of the exhaust system. Dampers at the apartment level and on top of each of the shafts restrict the exhaust flow.

When the building is operating without the mechanical ventilation system, the air mass flow distribution for windward side apartments on different floors follows a predictable pattern (Figure 12). With increasing wind speed, the distribution of infiltration becomes more pronounced, showing a minimum at the level of the third floor and a maximum at the 11th floor. The leeward side apartments do not experience any infiltration.

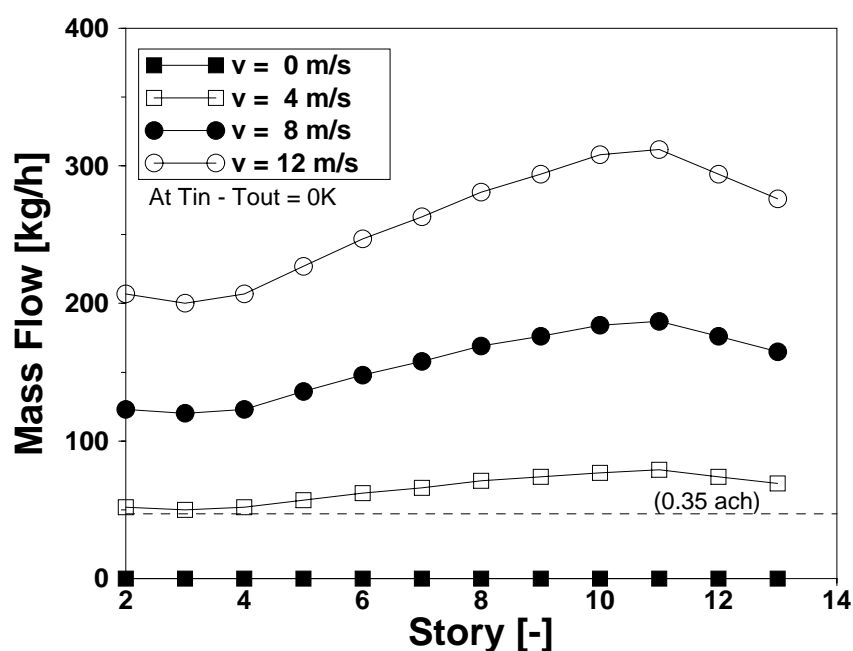


Figure 12. Mass air flow into **windward** apartments at different wind speeds, with no inside/outside temperature difference and the mechanical ventilation system **off**.

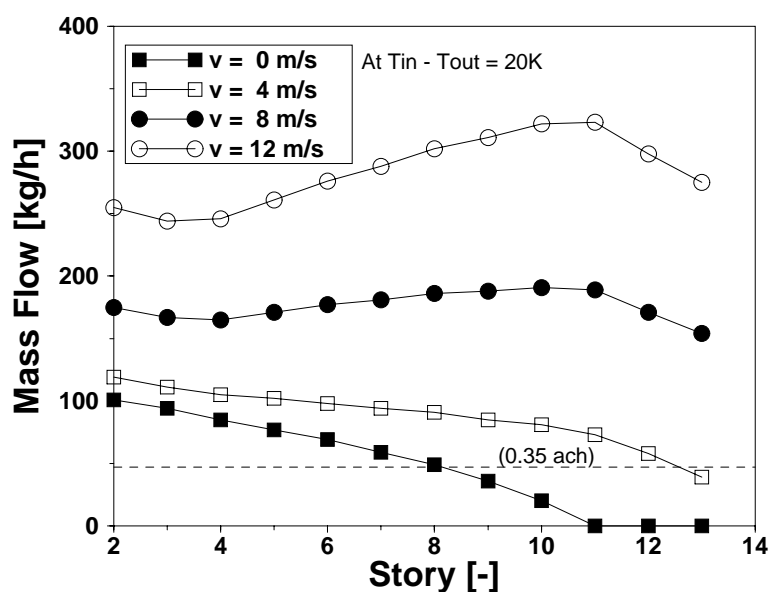


Figure 13. Mass air flow into **windward** apartments, at different wind speeds with an inside/outside temperature difference of 20 K and the mechanical ventilation system **off**.

With a larger inside/outside temperature difference of 20 °C and zero wind speed, the air flow for the windward apartments decreases with height above ground from 100 kg/h (50 cfm) on the second floor to zero at the level of the 11th floor. With increasing wind speed the air flow curves show a more balanced air flow distribution until the velocity driven air flows override the stack effect (Figure 13). As the pressures forcing the air flow can be added, the air flows for any given wind speed are higher if stack pressure is present.

The air flows for the leeward side is shown in Figure 14. With increasing wind speed the air flow entering the apartments through the outside wall is getting smaller. The zero wind speed curve is the same for the windward side and the leeward side. The top floors do not experience any infiltration. Higher wind speeds cause higher negative pressures on the facade, which lower the level for the neutral pressure. At wind speeds of 12 m/s no infiltration occurs at the apartments facing the leeward side.

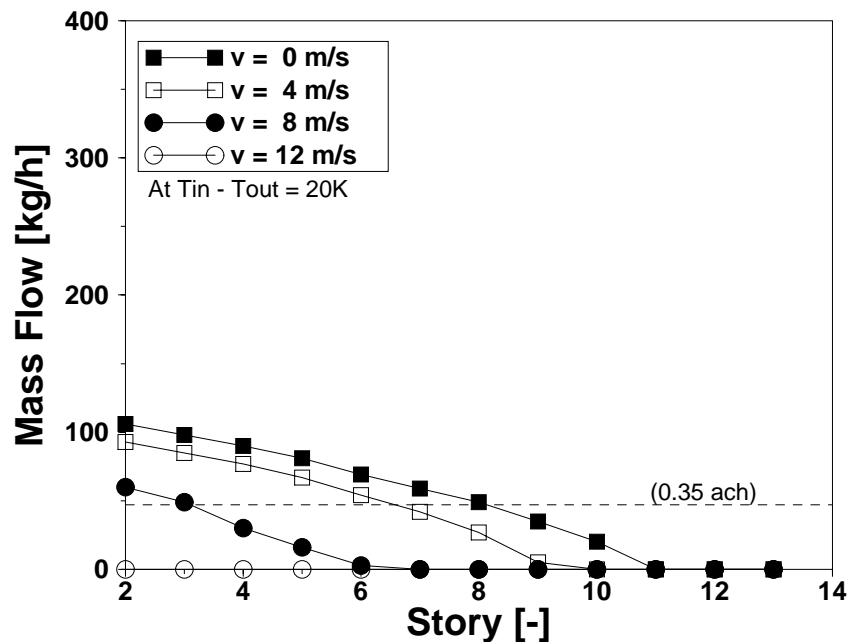


Figure 14. Mass air flow into **leeward** apartments, at different wind speeds with an inside/outside temperature difference of 20 K and the mechanical ventilation system **off**.

Air flows into the apartments are slightly higher when the ventilation system is in operation. Figure 15 shows the air flows entering the apartments located on the windward side through the facade for different wind speeds when no stack effect is present. At low wind conditions, infiltration is almost independent of the height above ground. With higher wind speeds, we see that the infiltration flows follow the wind pressure profile.

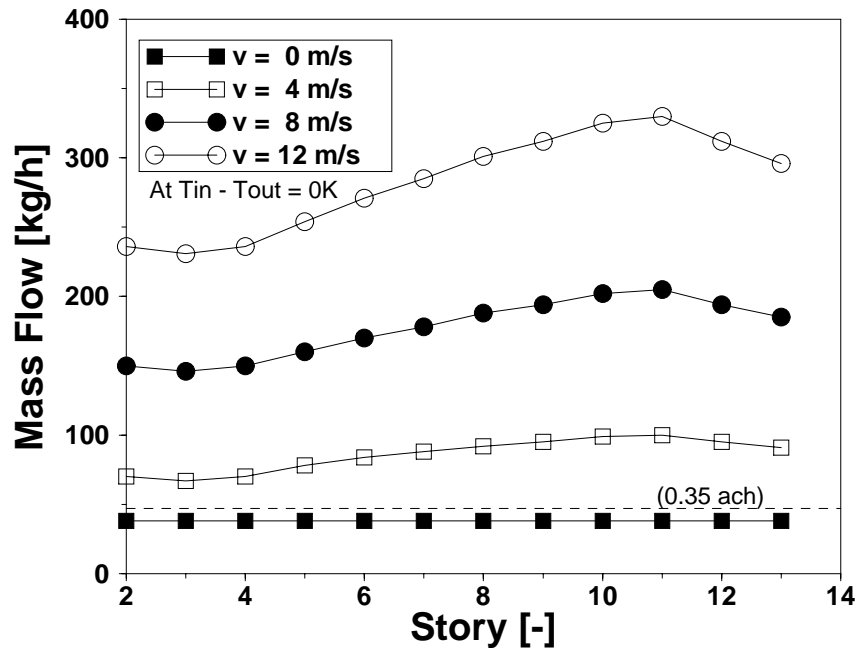


Figure 15. Mass air flow into **windward** apartments at different wind speeds, with no inside/outside temperature difference and the mechanical ventilation system **on**.

The infiltration for the leeward side apartments is quite different (see Fig. 16). For the case of no wind and no inside/outside temperature difference, approximately 75 kg/h are sucked by the exhaust system into the apartment through the exterior building components. With increasing wind speeds, the infiltration is reduced. At wind speeds of 4 m/s, approximately 0.35 ACH are still reached, but with higher wind speeds, the infiltration rate is further reduced, until no outside air enters the apartments when the wind velocity exceeds 12 m/s.

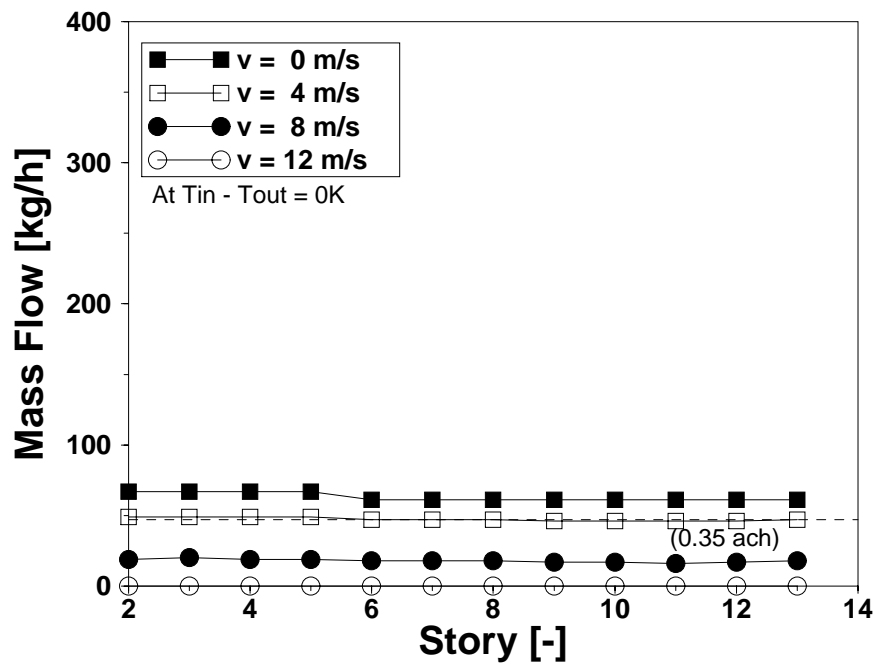


Figure 16. Mass air flow into **leeward** apartments at different wind speeds, with no inside/outside temperature difference and the mechanical ventilation system **on**.

The ventilation system is designed to provide the necessary “fresh” air by means of supplying the air to the corridor. The direction of the air flow through the doorway of the apartment determines whether the supplied air is entering the apartments. For the two higher wind speeds, the air flow passing through the doorways are shown for the apartments on both sides of the corridor (Figure 17). We see, that at higher wind speeds the windward side apartments do not receive any of the air supplied to the corridor. At lower wind speeds, the windward side apartments located on the lower floors participate slightly in the air exchange provided by the supply system. This means, that at lower wind speeds about all the air entering through the facade is being exhausted directly into the vertical exhaust shafts. At higher wind speeds, air from these apartments is forced into the corridor.

All leeward side apartments receive between 50 and 75 kg/h air from the corridor (see Figure 17). With higher wind speeds, the amount of air entering from the corridor increases, however, the air flow being supplied to the corridor via the windward side

apartments is much bigger than the air entering the leeward side apartments. The excess air is leaving the corridor through the elevator shaft. The pressure difference between the corridor and the air intake on the roof could significantly reduce the supply air flow to the corridors.

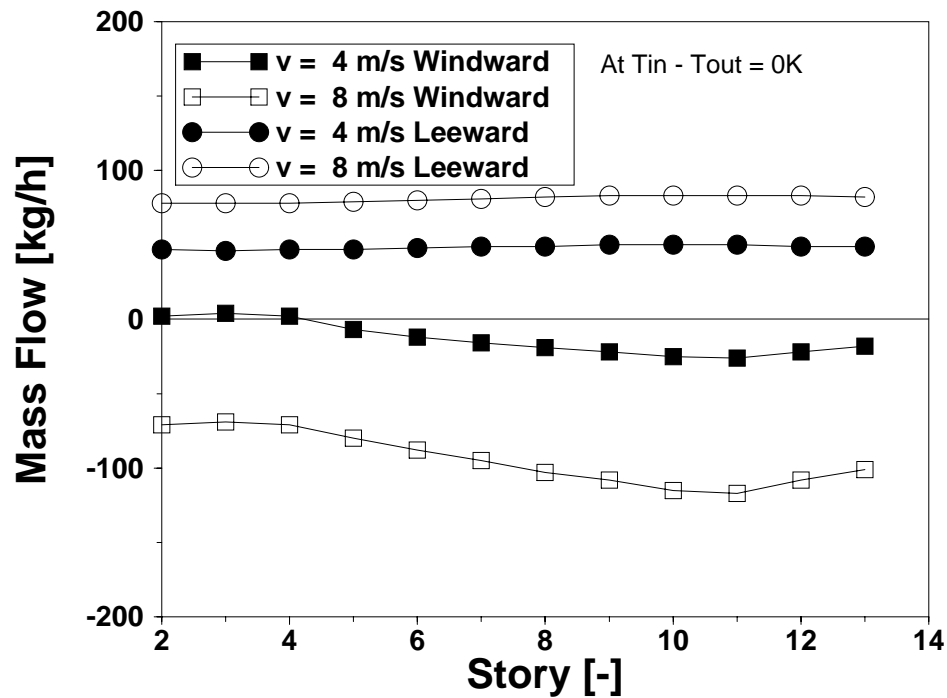


Figure 17. Mass air flow between the apartments and the corridor at different wind speeds and no inside/outside temperature difference, for all apartments and with the mechanical ventilation system on.

With larger temperature differences between inside and outside present (winter case), the infiltration flows for the lower windward side apartments increase significantly. As a consequence, flows from windward side apartments to the corridor will increase for the lower storeys (see Figure 18). Due to the stack effect, even leeward side apartments on floors 2 and 3 contribute to the excess flow of the corridors. Higher up in the building, leeward side apartments receive air from the corridor while windward side apartments exhaust air into the corridor. With increasing temperature difference, the stack effect is amplified.

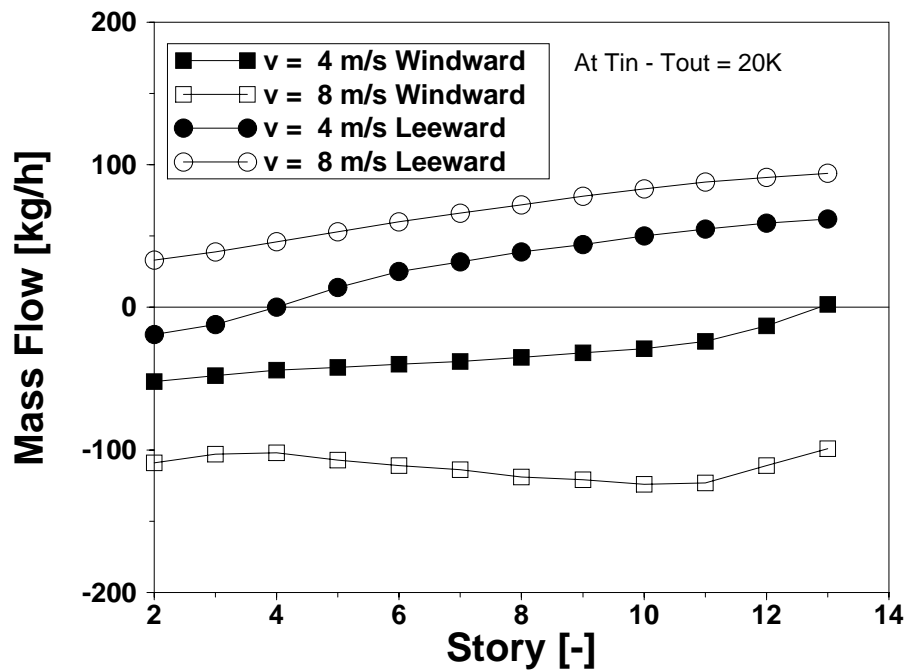


Figure 18. Mass air flow between the apartments and the corridor at different wind speeds and an inside/outside temperature difference of 20 K, for all apartments and with the mechanical ventilation system on.

With the mechanical system operating, the apartments on the leeward side have significantly higher ventilation rates than the apartments on the windward side, particularly in the case of high wind speeds. When the wind is parallel to the building, the mechanical ventilation system is needed in order to ensure proper ventilation to the apartments.

4.0 Conclusions

In any study of a building as complex as a highrise apartment it is important to validate the findings using as many techniques as possible. In the case of the Margolis Apartments we have been fortunate to have different data sources: leakage measurements, pressure tests and air infiltration measurements which have all been used to validate the model. Because comparisons between the model and measurement data agree well in several areas, such as similar directions and

magnitude of pressure differences across apartment doors and stairwell doors, we have a high degree of confidence in the simulation results.

Based on our analysis of the air flow simulations we see that the ventilation to the individual units varies considerably. With the mechanical ventilation system disabled (pre-retrofit case), units at the lower level of the building had adequate ventilation only on days with high temperature differences, while units on higher floors had no ventilation at all. Units facing the windward side were over-ventilated when the building experienced wind directions between west and north. At the same time, leeward side upper apartments would not experience any fresh air--air flows would enter the apartments from the corridor and exit through the exhaust shafts and the cracks in the facade. Even with the mechanical ventilation system operating, we found wide variation in the air flows to the individual apartments.

A fundamental issue here is the design question of how to best supply ventilation to individual apartments in a highrise building. Using the corridor as the supply route has several challenges, including the control of the temperature of the supply air, the temperature of the corridor, the opening from the corridor to the apartment, tenant comfort and the balance between supply and apartment exhaust.

A major conclusion from our measurements and simulations is that each apartment has to be supplied with ventilation air directly. Pressure drops of the system have to be high enough to overcome natural forces to be able to ensure an even distribution of ventilation air. If ventilation air is supplied directly to the individual apartments, the apartments should be uncoupled from the rest of the building by tight apartment doors. This condition not only decreases the impact of natural forces on the distribution of ventilation air, but also reduces the disturbance to tenants of odors or noise from other apartments. In winter, supply air has to be preheated to avoid unpleasant cold drafts. Supply air provided by vents in the envelope should either be preheated by heating elements in the vent itself, or be supplied adjacent to heating sources. Ducted supply air should be preheated in the central unit.

On the exhaust side, studies have shown that when apartment occupants have local control over bathroom and kitchen exhaust, they use them less than one hour per day, if at all (Shapiro-Baruch, 1993), which makes it difficult to size the supply ventilation system. Continuous exhaust ventilation, however, presents the possibility of over ventilation and unnecessary use of energy.

Efforts to improve the energy efficiency of high-rise apartment buildings have been frustrated because of the lack of knowledge on air flows for individual apartments. Ventilation rates for individual apartments vary greatly due to height, orientation, and wind speed and outdoor temperature. Any recommendations for reducing air leakage will have to take these variables into account, so that efforts to tighten the shell for energy efficiency do not create health and comfort problems for the residents.

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